The Cassini Travel Guide

to Cassini’s Flyby of Earth

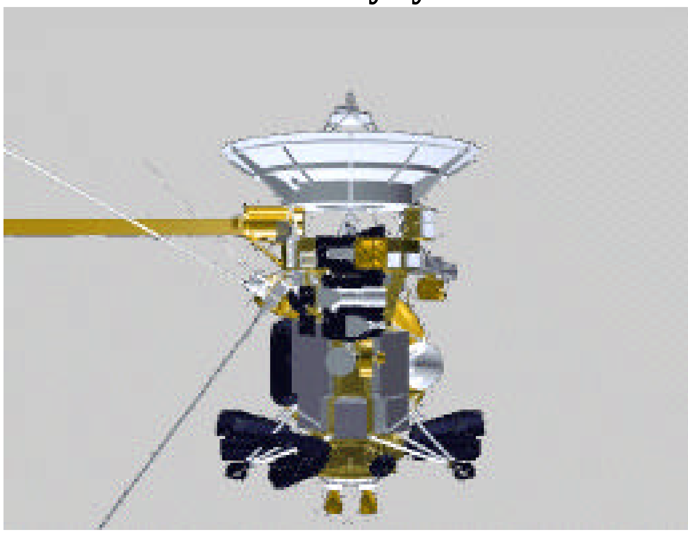


Figure 1. The Cassini Spacecraft

You are there

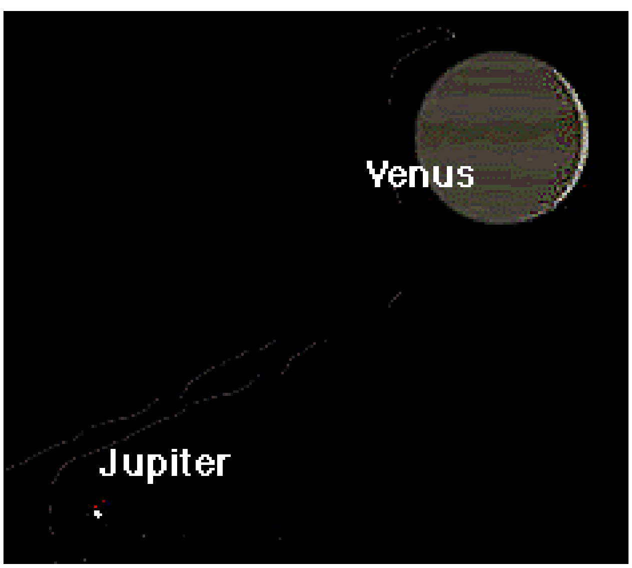
Picture in your mind’s eye: it’s June, 1999, and you are right there, beside the Cassini spacecraft hanging weightless, following its trajectory deep in interplanetary space (never mind the hostile environment preventing you from really being there). Cassini's launch is years behind. There’s no sense of movement, and the two-story-tall spacecraft just seems to be quiet and motionless, except for a quick flash now from of one of the small rocket thrusters on booms near the aft end. A flash repeats once every few hours, to keep the massive robot pointed in the right direction.

You notice a decorated pocket on one side of the spacecraft. It contains the signatures of over six hundred thousand people. Yours is among them, if you sent it by the deadline late in 1997.

There’s no planet nearby; nothing to give any hint of Cassini’s tremendous velocity. There is only the quiet ocean of space: nothingness in most directions, punctuated by thousands of tiny bright stars, looking like the bright points of light you see on the clearest, darkest nights on Earth. But from here beside Cassini they’re clearer, brighter, and never twinkling. Our local star the Sun dominates the scene in one direction, although when you shade it from view the starry darkness returns. The sunlight is hot, so the spacecraft keeps its big, white dish antenna pointed right at it. The resulting shade protects the rest of the craft from overheating. Onboard heaters and blankets are sufficient to prevent freeze damage in the cold shadow.

The sensation is that of falling, yet there is no "up" from which you are falling, nor any "down" you're falling toward. Oddly, even when Cassini increases its speed as the result of a "gravity assist" planet flyby, there's no sense of acceleration at all.

One of the many thousands of points of light surrounding Cassini is our home planet -- Earth. The radio signals Cassini constantly transmits are received there, when busy tracking schedules permit. And on that tiny bluish dot, engineers and scientists work on plans for Cassini's future activities. Radioed commands arrive at Cassini's antenna, invisibly, silently. They are recognized, processed, stored, silently aboard. As Cassini's counting clock arrives at times that match certain commands, they execute, most of them unnoticeably from beside the spacecraft. But once in a while there's some visible activity. When the Magnetometer Boom Deployment commands execute, from your imaginary perspective near Cassini you'll see the springy boom unravel from its meter-long cannister, within minutes extending to an uncanny 11 meters, holding sensitive field sensing instruments away from magnetic noise generated by the spacecraft. This deployment occurs before Earth flyby, so the magnetometers can be calibrated against the well-known field which shields life on Earth against particles from its parent star.



At first, Venus isn't very convenient to see from beside Cassini: it appears to be very close to the Sun. On June 6 it is *directly* between Cassini and the Sun, with only the planet's far side illuminated: you're approaching Venus from its night side. By early morning on June 23, Venus appears the size of the Moon, from Cassini, and bright Jupiter is close to it in the sky. Venus is a very thin crescent in its "new" phase, but growing larger and larger by the hour: now your tremendous velocity is beginning to show. If you hold up your hand to shield the Sun and the bright crescent Venus, you'll see the background stars appear to be moving relative to the planet, faster and faster, as this Earth-size world approaches. Late the next day, the lifeless world has grown to dominate the scene, much as the blue Earth looms close to astronauts aboard Mir or the Space Shuttle. As you recede from closest approach, Venus shrinks back down to the size of the Moon again by 8 am on June 26, but this time it's extremely bright: you're looking at more than half its illuminated face, and Venus' clouds make it ten times brighter than the Moon could ever be.

Looking away from Venus on the fourth of July, you can see your new target as bright as the Evening star, with the Moon visible near it. At 5 am August 17, Earth is as big as a Full Moon, but it's five times as bright! The next day the home planet fleetingly dominates the scene, only to fall away forever as you sail on into the outer solar system. Following these encounters with Venus and Earth, there won't be much change in scenery until around winter solstice of 2000 when Jupiter will have grown to the size of a full Moon just before flyby.

We invite you to come along on this fascinating flight. Since you can't actually fly along with the spacecraft, we'll try and help in every way to make sure you're as involved as you can be. It's a journey we hope you'll enjoy.

Some Background on Cassini

Cassini's Objectives

The Cassini Mission is designed to carry out a detailed study of Saturn, its atmosphere, its rings, its magnetosphere, its icy satellites, and its largest satellite Titan. The Cassini Orbiter will carry the Huygens Probe into orbit around Saturn in 2004, and then will release it, to enter the dense, hazy atmosphere of Titan. Cassini will continue to orbit Saturn, gathering data for at least four years.

Launch

Cassini's seven-year journey to the ringed planet Saturn began at 4:43 am EDT with the flawless liftoff of its Titan IVB/Centaur from Cape Canaveral, Florida, carrying the Cassini Orbiter and its attached Huygens Probe. The relatively few minutes of Cassini's launch period supplied virtually all the propulsive power needed for Cassini's flight. The spacecraft will be free-falling for all of its nearly seven year cruise, except for some infrequent, small propulsive maneuvers (Trajectory Correction Maneuvers or TCMs) which make tiny adjustments in course or speed.

Cassini's Trajectory

Cassini's launch vehicle didn't speed it on its way toward Saturn, it slowed it down! Before launch, Cassini was, of course, orbiting the Sun, just as you and I are right now. The Titan-IV launch and the first firing of its Centaur upper stage simply separated Cassini from the Earth. It still had the same momentum going around the Sun that it had while still attached by gravity to Earth's surface. Then the Centaur fired again, slowing down the spacecraft, so that it would begin to lag a little behind Earth in its travel around the Sun. The amount of slowing given to Cassini was just enough so that as it continued around the Sun, it would fall in about as far as the orbit of Venus.

Why does Cassini fly by Venus and Earth?

Cassini's flight path was chosen to orbit the Sun twice before heading into the outer solar system. By flying close behind Venus and Earth in their travel around the Sun, Cassini exchanged momentum with these planets. This results in enough added momentum for Cassini to leave the inner solar system, eventually to reach Saturn in 2004. Cassini will also fly behind Jupiter as it orbits the Sun. The added velocity obtained for Cassini, by doing this, shaves over two years from its flight time between Jupiter and Saturn.

Gravity Assist

How can gravity assist a spacecraft? Let's follow Cassini's flight path in Figure 2, the Trajectory diagram. From **point 1** notice Cassini's arc drops inward toward the Sun slightly. This is the result of the second firing of the Centaur upper stage on the morning of launch. It slowed the spacecraft down a bit, compared with Earth's velocity around the Sun.

At point 2, Cassini flies behind Venus. The planet, of course pulls the spacecraft with its gravity. But the spacecraft has gravity too, and pulls on the planet a minute amount! This causes Venus to lose a little energy from its solar orbit, while Cassini gains a lot. The resulting arc extends out past the orbit of Mars (Mars's orbit is not depicted). You can think of it as a ping-pong ball hitting an electric fan. The fan blades, whirling around the motor, have lots of angular momentum (as do the planets as they go around the Sun). When the ping-pong ball hits a fan blade, it slows the blade a very small amount, but the ping-pong ball gains lots of speed from the encounter. The ball connects with the blade mechanically, while a spacecraft connects with a planet via mutual gravitation.

At **point 3**, the spacecraft fires its main rocket engine to target for the next planet flybys. Cassini's path continues to **point 4** in the illustration as it flies behind Venus again. At **point 5**, Cassini steals energy from Earth's solar orbit, and the spacecraft's resulting arc reaches all the way to Saturn. The Jupiter flyby reduces travel time to the ringed planet.

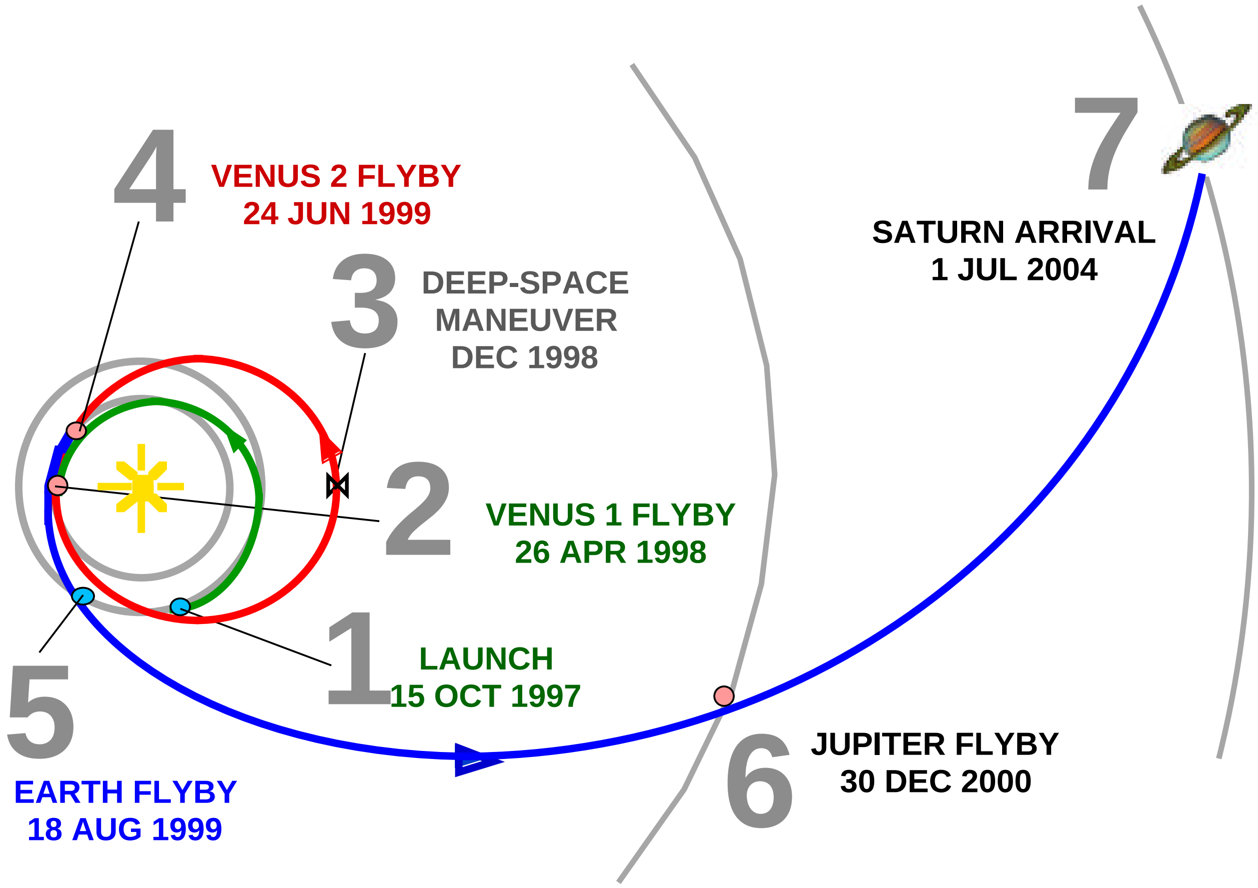


Figure 2. Cassini's Trajectory

The Deep Space Network

Our Long-Distance Company

All robotic interplanetary spacecraft communicate with the engineers and scientists on Earth by means of the Deep Space Network (DSN). The DSN, managed for NASA by JPL, comprises three Deep Space Communications Complexes. One is located in the California desert near Barstow, one is located near Madrid, Spain, and one is near Canberra, Australia, because these places are located about equidistantly around the world. As the Earth turns, at least one complex can "see" a spacecraft at any given time.

The DSN’s giant dish antennas are scheduled to track various spacecraft, including Cassini, for the purpose of obtaining tracking data for navigation, telemetry data for science and engineering, radio science data, and sending command data from the flight project to the spacecraft.

Earth Flyby

Timeline of Activities

It only takes 54 days for Cassini to reach Earth from Venus. For a day-to-day description of the activities surrounding the Venus-2 flyby, have a look at Figure 3, the simplified timeline. It was created during the development of the sequence of commands, named C-15, which the spacecraft executes during the Earth flyby period. Dozens of routine background engineering activities and conditions were removed to make it easier to see and discuss the ones of major interest. The week numbers along the top refer to the week in 1999. The numbers along the bottom, beginning with 193, indicate the day of year 1999; the L+ numbers in parentheses indicate the number of days since Launch.

The first activity inside the timeline is the Trajectory Correction Maneuver TCM 10, which begins to bring the flyby aim point in towards Earth. At this time, commands uplinked to the spacecraft cause it to turn to the proper attitude and fire the small thrusters for a few minutes. These TCMs, as mentioned, use the small thrusters, known as the Reaction Control System (RCS), rather than the large 400-Newton (100-pound thrust) main engine. The RCS thrusters are rated at less than one Newton each. Four of them fire continuously to provide the small amount of thrust required for an RCS TCM.

The next activity is a Periodic Instrument Maintenance (PIM). Like the PEM, Periodic Engineering Maintenance, described in the Cassini Venus Travel Guide, this routine activity is scheduled every three months. A PIM turns on all the science instruments on the spacecraft and downlinks a small amount of data from each so that their health can be verified.

All during this period, as shown in the timeline by the central grey band, the Cosmic Dust Analyzer (CDA) is operating, measuring the number of particles that hit the instrument. This scientific instrument, designed primarily for use at Saturn but operable nearly continuously in cruise, can determine many properties of dust particles, including their direction of travel, mass, and even their chemical composition. Obtaining these measurements in the inner solar system adds to knowledge of the environment. Typically, only a few particles are sensed over a period of several weeks along Cassini’s trajectory in the inner solar system.

The next two TCMs, TCM 11 and TCM 12, bring the flyby aim point to the desired altitude for passage by Earth. TCM 13, after Earth flyby, serves to “clean up” any residual error in Cassini’s trajectory into the outer solar system. Performing this maneuver early in the post-Earth period allow more "leverage," that is using less propellant to correct the course than if it were performed later on when the spacecraft is well on its way to Jupiter and Saturn.

Cassini's science instruments will be obtaining data during the Earth encounter, much as they were during the Venus-2 encounter as described in the Cassini Venus Travel Guide. But there are some additional activities this time. Observations will be made of the Moon. The spacecraft will roll to an angle which protects the SRUs from the bright Earth and that allows the optical remote sensing instrument fields-of-view to pass across the lunar disk. This occurs about an hour and a half before closest approach, and will allow ISS, VIMS, and UVIS to obtain calibration data. Post-Earth science includes observation of the geomagnetic tail, the elongated teardrop of Earth's magnetic environment which streams away from the Sun.

The next activity is to re-establish a nominal long duration value for the Command Loss Timer, CLT, which had been set to a small value during the flyby period. The CLT is a software timer aboard the spacecraft which is reset to a large number of hours every time a command is received from the Earth. If for some reason the spacecraft has not received a command for the number of hours specified (during cruise, this value is typically 264 hours), the spacecraft will autonomously begin taking actions to make sure it has a functioning link to Earth. For example, if one of the receivers on the spacecraft were to fail, it could not receive commands, so it would switch to a spare radio receiver. For periods of high activity levels such as planet flybys, the CLT value is normally reduced, so that in the very unlikely event of a communications failure, recovery of a link to Earth won't take quite so long.

Following that is an activity labelled "CDS FSW Upload." The CDS is the Command and Data Subsystem, the "main" computer on board the spacecraft which recognizes commands from Earth and performs all the on-board data handling work. FSW stands for Flight Software. New software is being developed at JPL which will update and add capabilities to the CDS which are needed for the remainder of the cruise to Saturn. This software will be uplinked to the spacecraft during Week 34. Its function will be verified shortly thereafter.

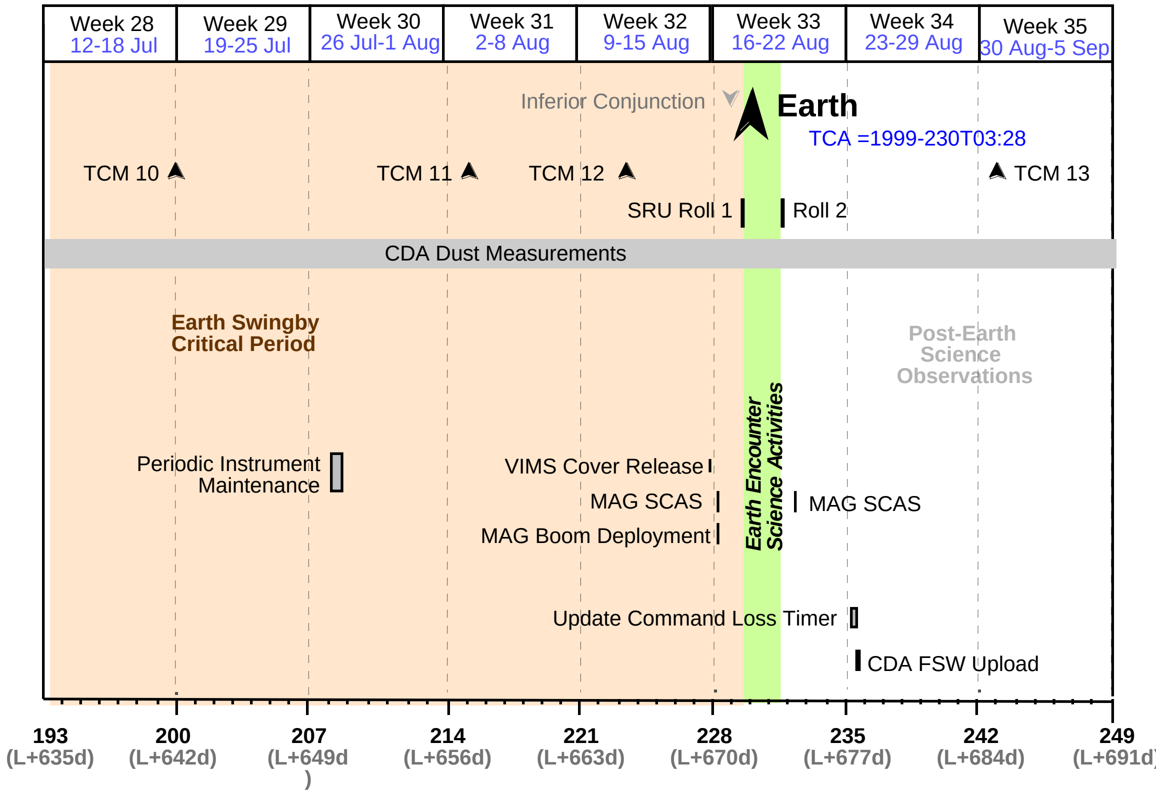


Figure 3. Earth Flyby Simplified Timeline

The Instrument Activity Timeline, Figure 4, illustrates details of the scientific instruments' events. Times of closest approach to the Moon and Earth, and the spacecraft's first roll, appear above the CDA activity already mentioned. Additional instrument activities appear below the CDA line.

The magnetometer boom (mag boom) will extend. The mag boom is stored inside a relatively small cannister, about half a meter in length. When it comes time for deployment just before Earth swingby, it will expand out from within the cannister to a length of 11 meters. The boom is made of springy fiberglass rods, not unlike fishing rod material. It is covered in multi-layer insulation blankets. A lanyard lets it unfurl at a controlled rate. Once extended, the boom holds its two magnetic field sensors out away from the spacecraft, so that they can concentrate on measuring the magnetic fields of planets at a distance from interfering magnetic fields on the spacecraft itself.

It is important to have the magnetometers deployed on their boom prior to Earth flyby, because the well-understood magnetic field of Earth can be used to calibrate the magnetometer instruments. Also, a self-contained magnetometer calibration activity occurs both before and after Earth flyby, indicated as "SCAS" on the timeline. SCAS stands for Spacecraft Calibration Subsystem. The SCAS generates magnetic fields of known strength and direction. For the first SCAS activity, the magnetometers can "see" the test fields as the instruments come twisting out of the cannister when the mag boom deploys. A final SCAS following Earth flyby completes the magnetometer calibration.

MIMI, the Magnetospheric Imaging Instrument, will be turned on about 16 hours before Earth closest approach in preparation for calibration. All MIMI's sensors will take advantage of the well-characterized environment around Earth to check out their response while making observations.

CAPS, the Cassini Plasma Spectrometer, will collect data in the well-characterized environment of Earth's magnetosphere to calibrate mass/charge and time-of-flight spectra. Specifically, this calibration will provide input on correct table values for onboard software which will be used to identify particle species from measured phase space data.

ISS, the Imaging Science instrument, will image the Moon in selected filter and polarizer combinations, for in-flight calibrations. The NAC will be targeted on an illuminated portion of the Moon away from the extreme limb or terminator. Stray-light calibration will also be performed by using the Moon when it is outside the field of view of the NAC. Dark frames will be taken to calibrate the images of the Moon.

The Moon will also provide a calibration target for UVIS, the UltraViolet Imaging Spectrograph. The instrument's far-UV and extreme-UV channels will have their stray-light characteristics measured, as their respective slits cross the Moon. The HDAC channel (HDAC stands for Hydrogen-Deuterium Absorption Cell) will be operating in photometry mode, to characterize its sensitivity using the Moon, which of course is a well-known source. After Earth closest approach, UVIS will join the fields and particles instruments as they collect data on the Earth's magnetic field including the extended geocoronal tail.

VIMS, the Visible and Infrared Mapping Spectrometer, will release covers which have been protecting its infrared optics and radiator until now. Stray light measurements will be made as the VIMS boresight approaches the Moon, to gather data on instrument operational characteristics near a bright body. When the Moon is in the VIMS field-of-view, full resolution images will be taken, to both calibrate the response function and validate that the covers have deployed properly. Another calibration opportunity will occur when the spacecraft is about one half hour past Earth closest approach. At this point, the spacecraft will be in position to allow the VIMS solar port to view the Moon. The solar port is an aperture on VIMS that permits it to look directly at the Sun. It will be used to study atmospheres and rings as they filter the sunlight.

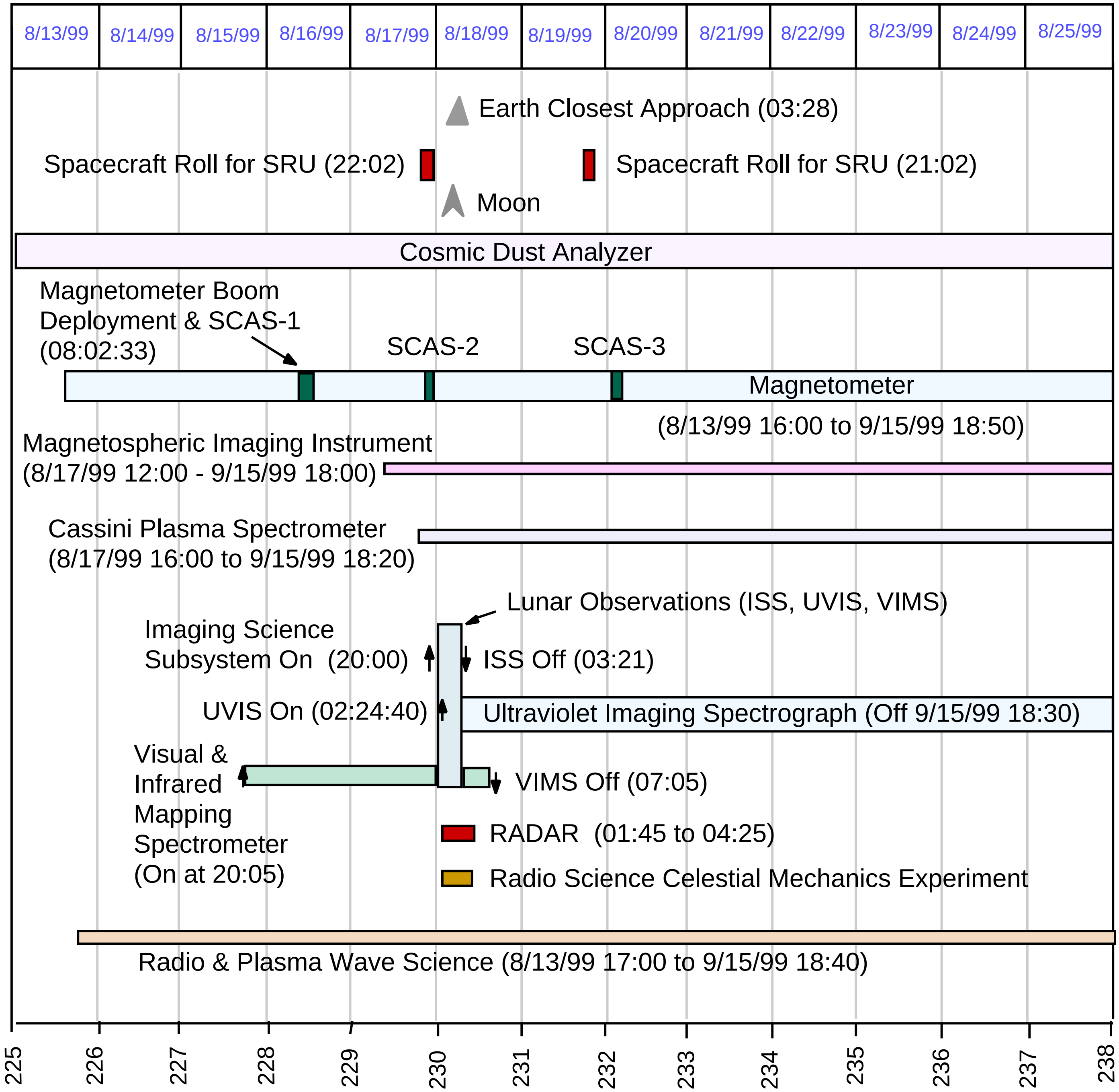


Figure 4. Earth Flyby Instrument Activity TImeline

Earth swingby represents the last opportunity prior to Saturn for a closed-loop test of RADAR. RADAR pulses will be transmitted and received when the Earth is in the maximum view of the sun-pointed HGA. Successful execution will avoid the need to repeat the activity at Titan, which would take away from RADAR's collecting of science data there.

Cassini's Radio Science experiment will be performing a celestial mechanics experiment during Earth swingby. By precisely measuring the Doppler shift of Cassini's radio signal as the spacecraft responds to our planet's gravitational pull, Radio Science will refine knowledge of the Earth's mass. It also provides data for studies of forces acting on the spacecraft.

RPWS, the Radio and Plasma Wave Science instrument, will validate its capability to determine the propagation characteristics of low-frequency plasma waves and execute a test of its direction-finding capability as a dry-run to ensure a successful direction finding calibration at Jupiter.

The fields and particles instruments will continue to collect data as the spacecraft recedes from Earth, through opposition, the period when Cassini appears opposite the Sun in the sky as seen from Earth. These instruments will attempt to detect the edges of the geomagnetic tail. In addition to the fields and particles instruments, UVIS, which is an optical instrument, will be observing the ultraviolet emissions generated as the geomagnetic tail interacts with the solar wind. The geometry of opposition, which occurs in September 1999, permits use of the high-gain (main) antenna for communications, while at the same time shading the spacecraft from sunlight.

Trajectory Correction Maneuvers (TCMs) and targeting strategy

Cassini is powered by plutonium-fueled (Pu238) RTGs, Radioisotope Thermoelectric Generators, which generate electricity using no moving parts. At no time is the spacecraft ever targeted directly toward Earth. Only over the course of three TCMs is the aim point brought closer to an aimpoint above the Earth, in order to fly by the planet at an altitude of about 1166 km.

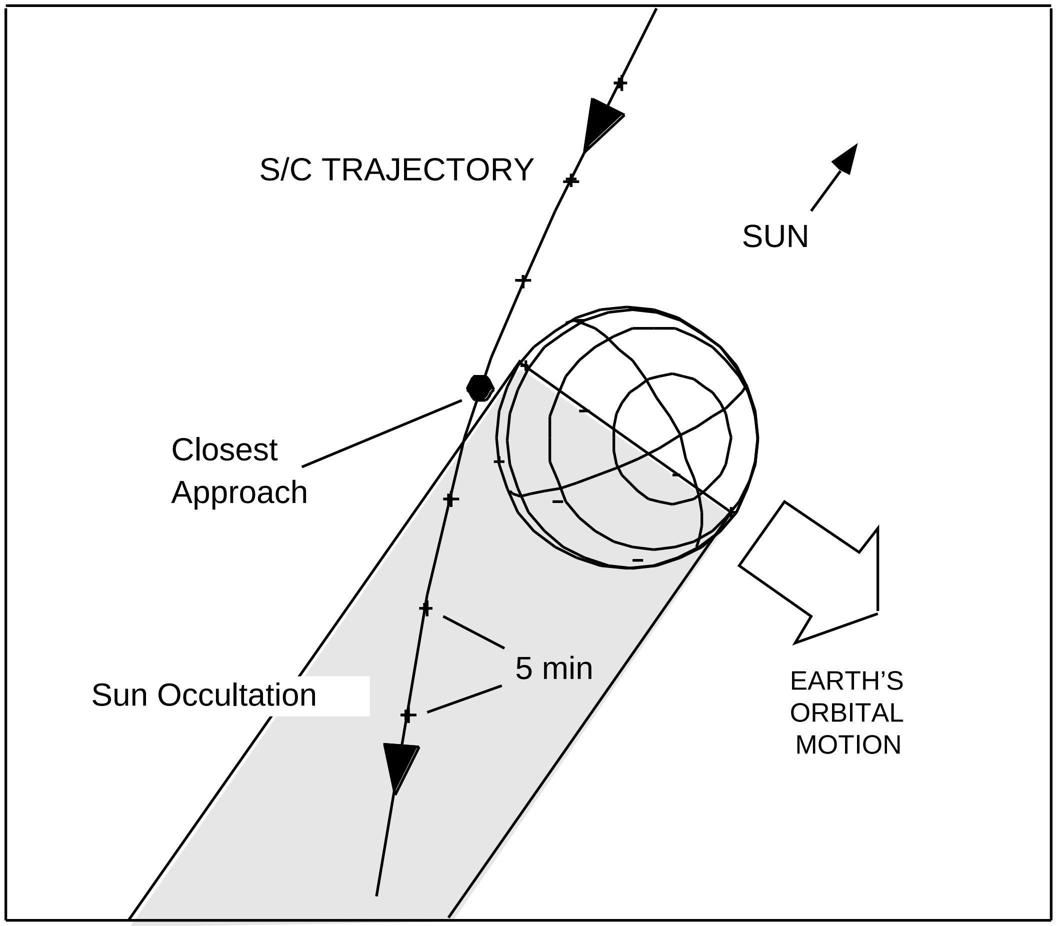
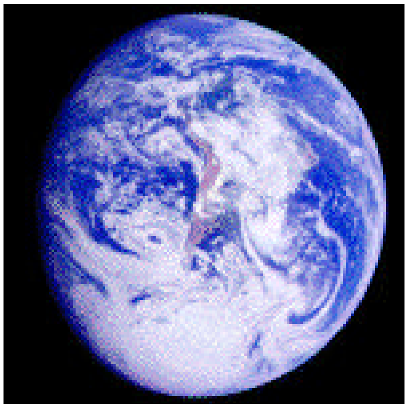


Figure 5. Earth Flyby Geometry

Flight path by Earth

Figure 5 illustrates the Earth flyby geometry. We're looking towards the south, that is, generally down on Earth's northern hemisphere. Note the direction to the Sun: Our planet is moving in its year-long orbit toward the lower right. You can see that the spacecraft flies close behind Earth in its path, once again "stealing" momentum from the planet via mutual gravitation. Tick marks identify 5-minute intervals. Cassini's closest approach to Earth occurs at 137 W longitude and 23.5 S latitude, over the South Pacific Ocean. Unlike the Venus flyby, Cassini does enter into shadow, or "Sun Occultation" behind the Earth.

Having absorbed momentum from both Venus and Earth, energy which the Titan-IVB/Centaur launch vehicle could not provide, Cassini finally has the velocity to reach Saturn. Even if Jupiter were not there for a flyby, Cassini could eventually complete a journey to the magnificent Saturnian system. But Jupiter is there, and so the Jupiter flyby in December, 2000, will speed the spacecraft to arrive at Saturn in July, 2004.



Earth Vitals
Earth is the third planet from the Sun and the fifth largest:

Orbit:	149,600,000 km (1.00 AU) from Sun
Diameter:	12,756.3 km
Mass:	5.9736e24 kg

The Moon
The Moon is the only natural satellite of Earth:

Orbit:	384,500 km from Earth
Diameter:	3476 km
Mass:	7.35e22 kg

On To Jupiter And Saturn

Planning for science observations has begun for Cassini's flyby of Jupiter. Science observations will begin in earnest two years prior to Saturn arrival, and continue in orbit at Saturn for a prime mission of four years. Cassini's initial approach offers the only opportunity to observe the small satellite Phoebe, which orbits in a retrograde direction. Cassini's orbit insertion around Saturn takes it closer than ever to the planet for a unique view of its rings. The first orbit provides an opportunity to release the Huygens Probe to study the atmosphere and surface of Titan.

Some World-Wide Web references

If you have access to the Internet, be sure to join us on this journey to tour the Saturnian system, and to explore related areas. If you don't have internet access at home or at work, you may be able to find access from a public library or university near you.

- Visit the Cassini web site, **http://www.jpl.nasa.gov/cassini**, where all the latest information may be found about the mission's progress, as well as descriptions of the spacecraft, the Huygens Probe, and every aspect of its journey.
- The Solar System Simulator, **http://space.jpl.nasa.gov**, will help you "fly along" with Cassini or to see any solar system body from any other. Be sure to select the view "from the Cassini spacecraft" to see what Cassini is "seeing."
- The Nine Planets, **http://seds.lpl.arizona.edu/billa/tnp**, offers all the latest information about each of the bodies in our solar system.
- The Basics of Space Flight, **http://www.jpl.nasa.gov/basics**, offers a broad overview of the many aspects of interplanetary robotic spaceflight.

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